

Very High Energy γ -ray observations of Mrk 501 using TACTIC imaging γ -ray telescope during 2005-06

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Abstract. In this paper we report on the Markarian 501 results obtained during our TeV γ -ray observations from March 11 to May 12, 2005 and February 28 to May 7, 2006 for 112.5 hours with the TACTIC γ -ray telescope. During 2005 observations for 45.7 hours, the source was found to be in a low state and we have placed an upper limit of 4.62×10^{-12} photons $\text{cm}^{-2} \text{s}^{-1}$ at 3σ level on the integrated TeV γ -ray flux above 1 TeV from the source direction. However, during the 2006 observations for 66.8h, detailed data analysis revealed the presence of a TeV γ -ray signal from the source with a statistical significance of 7.5σ above $E_\gamma \geq 1$ TeV. The time averaged differential energy spectrum of the source in the energy range 1-11 TeV is found to match well with the power law function of the form ($d\Phi/dE = f_0 E^{-\Gamma}$) with $f_0 = (1.66 \pm 0.52) \times 10^{-11} \text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$ and $\Gamma = 2.80 \pm 0.27$.

1. Introduction

Markarian 501 (Mrk 501) is a BL Lacertae (BL Lac) object at $z = 0.034$ and was discovered as a γ -ray source at $E_\gamma \geq 350$ GeV by the Whipple collaboration [16] and subsequently confirmed by the HEGRA collaboration[6]. In March 1997 the source went into a highly variable and strong emission state with flux doubling times of less than 0.5 day [17]. The time period of the outburst coincided with the source visibility windows of several ground-based Imaging Atmospheric Cerenkov Telescopes (IACTs). Thus almost continuous monitoring of Mrk 501 in TeV γ -rays was possible with several IACTs (Whipple, HEGRA, CAT, TACTIC) located in the Northern Hemisphere and they detected an integral flux of up to roughly 10 times that from the Crab Nebula above 1 TeV[15]. All Sky Monitor (ASM) on board the *Rossi X-ray Timing Explorer* (RXTE), also reported the high X-ray activity of the source which started in March 1997 and

continued till October 1997 [7]. The EGRET observations did not result in any detection of the source in high-energy γ -ray range (30MeV -30GeV)[7] in 1997, though a year earlier, the same instrument had detected Mrk 501 at 5.2σ level for $E \geq 500$ MeV[11]. There was an indication that the average optical U-band flux was higher in the month of the peak γ -ray activity [17]. Observations of Mrk 501 during 1998-1999 following the major 1997 outburst phase, reveal a mean emission level of $\frac{1}{3}$ of the Crab Nebula flux at 1 TeV, a factor of 10 lower than the 1997 outburst. The VHE spectrum measured during this period is substantially softer (by 0.44 ± 0.1 in spectral index) than the 1997 time-averaged spectrum [1]. The CELESTE group has also detected a weak γ -ray signal from Mrk 501 (3.4σ) using a low threshold system at Themis during their 2000 observations[20]. In 2003-04 HESS observation of Mrk 501 at large-zenith angle range for 1.8 hours, resulted in a marginal detection (3.1σ) of the source[3]. The MAGIC group has reported detection of two flaring episodes from the source on June 30 and July 09, 2005 with flux values of 3.48 ± 0.10 and 3.12 ± 0.12 Crab units respectively [4]. Among a number of interesting source related features this group has unveiled are the detection of the IC peak in the SED for the most active nights, flux variability increase with energy and an intriguing 4 minute shift in time (on July 9, 2005) of the higher energy flare compared to lower energies.

2. Experimental Setup

The TACTIC atmospheric Cherenkov telescope is located at Mt. Abu (24.6° N, 72.7° E, 1300 m asl), a hill station in Western India. It uses a tessellated light-collector of $9.5 m^2$ area which is configured as a quasi-parabolic surface, yielding a measured spot-size of 0.3° for on-axis parallel rays. The PC-controlled 2-axes drive system gives a pointing / tracking accuracy of better than ± 3 arc-mins. The telescope deploys a 349-pixel, photomultiplier tube (PMT) based imaging camera with a uniform pixel resolution of $\sim 0.3^\circ$ and a field of view of $\sim 6^\circ \times 6^\circ$ to record images of atmospheric Cherenkov events produced by an incoming VHE cosmic-ray particle or a γ -ray photon. Present observations use the inner 225 pixels (15×15 matrix) of the camera for the event-trigger generation, based on the NNP (Nearest Neighbour Pair) topological logic. The data acquisition and control system of the telescope [22] has been designed around a network of PCs running the QNX real-time operating system. The details of the telescope functioning are presented elsewhere [12]. The telescope is sensitive to γ -rays above 1 TeV and can detect the Crab Nebula at 5σ significance level in 25 hours of ON source observation.

3. Mrk 501 Observations

TeV γ -ray observations of Mrk 501 presented in this paper were made with the TACTIC γ -ray telescope during two periods (1) 11 March to 12 May 2005 for 22 nights and (2)

28 February to 07 May 2006 for 33 nights, with a total observation time of 129.25 hours. The observations were carried out in tracking mode, where the source is tracked continuously without taking off- source data [16]. This observation mode improves the chances of recording possible flaring activity from the source direction. Details of the Mrk 501 observations with the TACTIC γ -ray telescope during 2005 and 2006 are given in Table 1. Several standard data quality checks have been used to evaluate the overall system behaviour and the general quality of the recorded data. These include conformity of the prompt coincidence rates with the expected zenith angle trend, compatibility of the arrival times of prompt coincidence events with the Poissonian statistics and the steady behaviour of the chance coincidence rate with time. After applying these cuts, we have selected good quality data sets of 45.7 and 66.8 hours for 2005 and 2006 observations respectively, details of which are given in Table 1.

4. Data Analysis and Results

4.1. Data Analysis Procedure

Detailed analysis of data recorded by an atmospheric Cherenkov telescope, involves a number of steps including filtering of night sky background light, accounting for the differences in the relative gains of the PMTs, finding Cherenkov image boundaries, image

Table 1. Observation log for Mrk 501

Year	Month	Observation Dates	Total Observation Time (h)	Selected Observation Time (h)
2005	Mar.	11, 13, 15, 17-20	11.6	8.5
2005	Apr.	05-10	17.0	15.9
2005	May	02, 05-12	33.8	21.6
2006	Feb.	28	2.0	2.0
2006	Mar.	1-8, 25-29, 30	28.6	28.6
2006	Apr.	1-6, 27-30	20.3	20.3
2006	May	01-07	15.9	15.9

Table 2. Cut Values used for Analysis

Parameters	Cut Values
Length	$0.11^\circ \leq L \leq (0.235 + 0.0265 * \log(\text{size}))^\circ$
Width	$0.065^\circ \leq W \leq (0.085 + 0.01200 * \log(\text{size}))^\circ$
Distance	$0.5^\circ \leq D \leq 1.27^\circ$
Size	$S \geq 350$
Alpha	$\alpha \leq 18^\circ$

parameterization, event selection etc. We have characterized each Cherenkov image by using a moment analysis methodology given in [10, 18]. The roughly elliptical shape of the image is described by the LENGTH and the WIDTH parameters and its location and orientation within the telescope field of view are given by DISTANCE and ALPHA parameters respectively. We also determine the two highest amplitude signals recorded by the PMTs (max1, max2) and the amount of light in the image (SIZE) along with FRAC2 which is the addition of two largest amplitude signals recorded by PMTs divided by the image size [21]. The standard Dynamic Supercuts [14] procedure is then used to separate γ -ray like images from the huge background of cosmic-rays. In this procedure, the image shape parameters LENGTH and WIDTH have been used as a function of the image SIZE so that energy dependence of these parameters can be taken into account. The γ -ray selection criteria (Table 2) used in this analysis have been obtained on the basis of dedicated Monte Carlo simulations carried out for the TACTIC telescope. Here, it may be noted that the cuts used in the present work are softer particularly in terms of size parameter as compared to those used in [23]. This is necessitated by the need to compensate for the seasonal effects on the energy threshold due to sky conditions at Mt. Abu. For several years we are observing VHE sources with the TACTIC telescope and find that the average winter sky (from November to February) is slightly better in terms of sky transparency as compared to that during summer months (March to May). The dynamic cuts applied in the present data analysis have also been validated by applying them to the Crab Nebula data collected by the telescope. The γ -ray signal extraction, from the recorded data on a particular TeV γ -ray source using a single imaging telescope is generally, presented by plotting the histogram of α parameter (defined as the angle between the major axis of the image and the line between the image centroid and camera center, when the source is aligned along the optical axis of the telescope and hence the source is always placed at the centre of the camera) after applying the set of image cuts listed in Table 2. α parameter distribution is expected to be flat for the isotropic background of cosmic ray events, whereas for the γ -ray signal events, the distribution is expected to show a peak at smaller α values. This range for the TACTIC telescope is $\alpha \leq 18^\circ$. The contribution of the background events is estimated from a reasonably flat α region from $27^\circ \leq \alpha \leq 81^\circ$. The number of γ -ray events is then calculated by subtracting the expected number of background events, calculated on the basis of the background region of the α distribution [8], from the γ -ray domain events. The reason for not including the α bin 18° - 27° in the background region is to ensure that the background level is not overestimated because of a possible spill over of γ -ray events into this bin. Also, the last bin has been dropped to make sure that underestimation of background level does not take place because of the truncation of the Cherenkov images recorded at the boundary of the imaging camera [8]. The significance of the excess events has been finally calculated by using the maximum likelihood ratio method of Li & Ma [13].

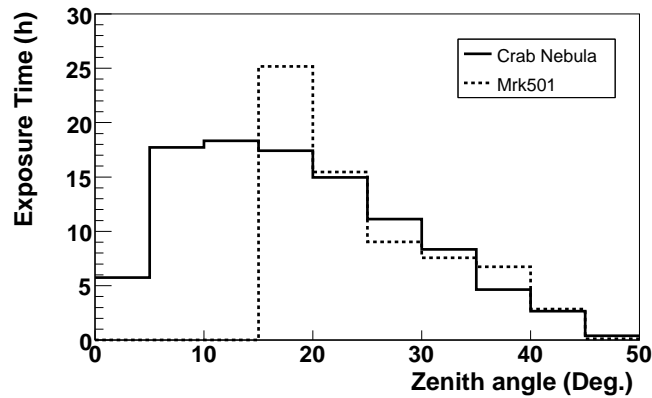


Figure 1. Histogram coverage of the zenith angle range from the Crab Nebula direction (solid line) observed for ~ 101.4 hours during Nov. 10, 2005 - Jan. 30, 2006 and from the Mrk 501 direction (dotted line) observed for 66.8 hours during Feb. 28, 2006 - May 7, 2006.

4.2. Validation of data analysis procedure using Crab Nebula data

In order to test the validity of the data analysis procedure and in particular, the energy estimation procedure, we have first analyzed the Crab Nebula data collected with the TACTIC imaging telescope for ~ 101.4 h during Nov 10, 2005 - Jan 30, 2006 with zenith range covered as shown in Figure 1. The corresponding α plot after using the Dynamic Supercuts procedure shown in Figure 2 clearly indicates significant excess of events in the first two bins having α range of $0^\circ - 18^\circ$, which is the γ -ray domain in the plot for the TACTIC system. In order to show that this distribution is flat in the absence of VHE γ -ray source, we have also shown the off-source data (for 12.5 hours only) α distribution in Figure 2 using the same procedure. The events selected after using the cuts mentioned earlier yield an excess of $\sim (839 \pm 89)$ γ -ray events with a statistical significance of $\sim 9.64\sigma$. Here, it may be noted that we have derived the background events from the on-source α plot while estimating γ -ray signal excess as we do not have the Crab off-source data of comparable duration with the same zenith angle coverage.

The corresponding average γ -ray rate turns out to be $\sim (8.27 \pm 0.88)/\text{h}$. The same data sample was then analyzed again after restricting the zenith angle of the observations to $15^\circ - 45^\circ$ (similar to the zenith angle range which Mrk 501 would cover as shown in Figure 1) so that the resulting γ -ray rate can be designated as a approximate reference of 1 Crab Unit (CU) while interpreting the Mrk 501 data. The analysis yielded an excess of $\sim (598 \pm 69)$ γ -ray events in an observation time of ~ 63.3 h with a corresponding γ -ray rate of $\sim (9.44 \pm 1.09)/\text{h}$, thus leading to the conversion: $1 \text{ CU} \approx (9.44 \pm 1.09)/\text{h}$. This increase in γ -ray rate is due to the superior γ -ray acceptance of Dynamic Supercuts at higher zenith angles which overcompensates the decrease in the rate due to increase in the threshold energy of the telescope.

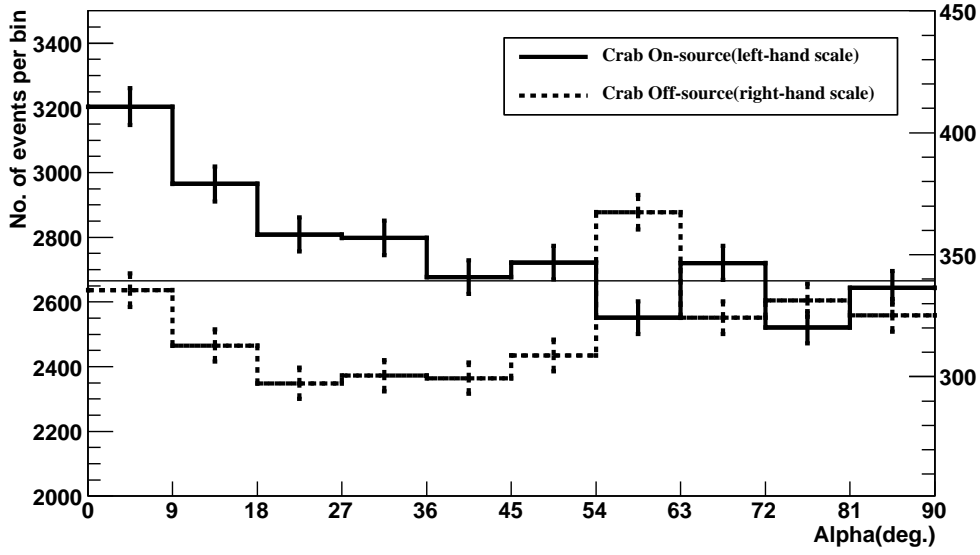


Figure 2. Distribution of image parameter ALPHA from the Crab Nebula direction (solid line and left-hand scale) observed for ~ 101.4 hours during Nov. 10, 2005 - Jan. 30, 2006. Horizontal line represents the background level per 9° bin derived using reasonably flat α region from $27^\circ \leq \alpha \leq 81^\circ$. Distribution of image parameter ALPHA is also shown (dotted line and right-hand scale) from the Crab Nebula off-source direction observed for ~ 12.5 hours during 2006. Error bars shown are for statistical errors only.

Further, the energy estimation procedure has been validated by deriving the Crab Nebula source energy spectrum using the above mentioned data of ~ 101.4 hours. The methodology used in deriving this energy spectrum is based on the Artificial Neural Network (ANN) technique and has been described in a detailed manner in [23].

The differential photon flux per energy bin has been computed using the formula

$$\frac{d\Phi}{dE}(E_i) = \frac{\Delta N_i}{\Delta E_i \sum_{j=1}^5 A_{i,j} \eta_{i,j} T_j} \quad (1)$$

where ΔN_i and $d\Phi(E_i)/dE$ are the number of events and the differential flux at energy E_i , measured in the i th energy bin ΔE_i and over the zenith angle range of 0° - 45° , respectively. T_j is the observation time in the j th zenith angle bin with corresponding energy dependent effective area ($A_{i,j}$) and γ -ray acceptance ($\eta_{i,j}$). The 5 zenith angle bins ($j=1-5$) used are 0° - 10° , 10° - 20° , 20° - 30° , 30° - 40° and 40° - 50° with simulation data available at $5^\circ, 15^\circ, 25^\circ, 35^\circ$ and 45° . The number of γ -ray events (ΔN_i) in a particular energy bin is calculated by subtracting the expected number of background events, calculated on the basis of background region, from the γ -ray domain events.

The γ -ray differential spectrum obtained after applying the Dynamic Supercuts and appropriate values of effective collection area and γ -ray acceptance efficiency (along

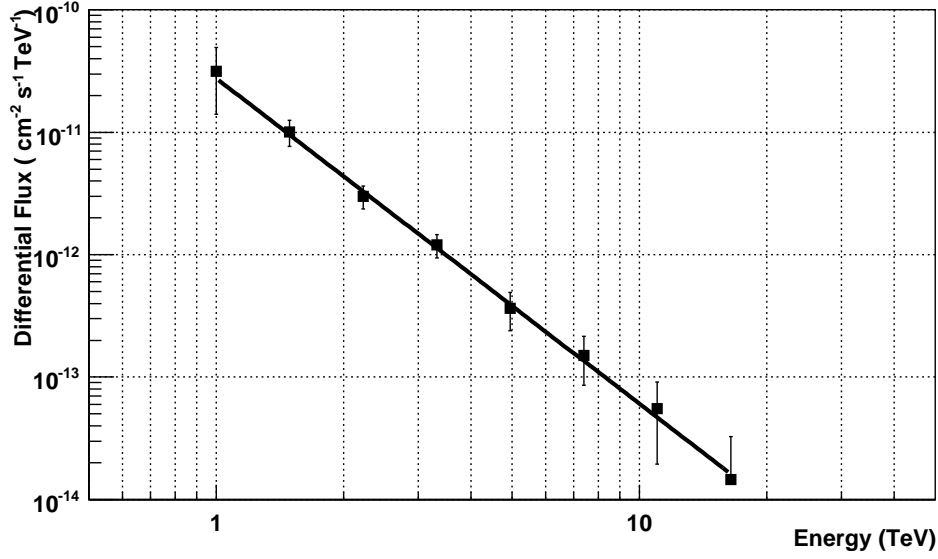


Figure 3. Differential energy spectrum of Crab Nebula as measured by the TACTIC telescope during 2005-06. Error bars shown are for statistical errors only.

Table 3. Crab Nebula differential energy spectrum data obtained during 2005-06 observations with the TACTIC telescope.

Energy (TeV)	Energy bin width (TeV)	Diff. flux photons $\text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$	Statistical error in flux photons $\text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$
1.000	0.403	3.165×10^{-11}	1.75×10^{-11}
1.492	0.601	1.01×10^{-11}	2.43×10^{-12}
2.226	0.896	3.00×10^{-12}	6.32×10^{-13}
3.320	1.337	1.19×10^{-12}	2.60×10^{-13}
4.953	1.994	3.66×10^{-13}	1.26×10^{-13}
7.389	2.975	1.5×10^{-13}	6.5×10^{-14}
11.023	4.439	5.54×10^{-14}	3.59×10^{-14}
16.445	6.622	1.45×10^{-14}	1.79×10^{-14}

with their energy and zenith angle dependence) is shown in Figure 3. Since energy spectrum determination also requires an 'instrument calibration' factor for converting image size in CDC counts to number of photoelectrons, this was determined by using the excess noise factor method. The analysis of relative calibration data yields a value of $1\text{pe} \cong (6.5 \pm 1.2) \text{ CDC}$ for this conversion factor when an average value of ~ 1.7 is used for excess noise factor of the photomultiplier tubes.

The differential energy spectrum of the Crab Nebula shown in Figure 3 is of the form of a power law ($d\Phi/dE = f_0 E^{-\Gamma}$) with $f_0 = (2.74 \pm 0.64) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$

and $\Gamma = 2.65 \pm 0.19$. The fit has a $\chi^2/dof = 0.53/6$ with a corresponding probability of 0.997. The low value of the reduced χ^2 may be due to overestimation of the errors in the present measurements. The errors in the flux constant and the spectral index are standard errors. The work on detailed understanding of the telescope systematics is in progress, our preliminary estimates for the Crab Nebula spectrum indicate that the systematic errors in flux and the spectral index are $\leq \pm 40\%$ and $\leq \pm 0.42$, respectively. Excellent matching of this spectrum with that obtained by the Whipple and HEGRA groups reassures that the procedure followed by us for obtaining the energy spectrum of a γ -ray source is quite reliable. Matching of the Crab Nebula spectrum also ensures that we have tested the full analysis chain and the stability of the TACTIC system directly by using γ -rays from the standard candle γ -ray source. The details of the derived Crab energy spectrum have been tabulated in Table 3, wherein the energy binwidth is chosen in such a way that when it is divided by the corresponding energy it yields a constant value of 0.40.

The data analysis procedure described above was applied to the Mrk 501 datasets, obtained using the TACTIC telescope during 2005-06. These datasets have been rigorously analysed, on a yearly as well as monthly observation spell basis, for the presence of TeV γ -ray signal. We have also searched, for possible strong TeV flaring episodes during the epochs of our observations and have further divided the data on a nightly basis and repeated the same analysis procedure.

4.3. Results of Mrk 501 2005 data analysis

When all the data recorded during the year 2005 are analysed together, the corresponding results obtained are shown in Figure 4a, wherein the histogram of the alpha parameter has been plotted after having applied shape and orientation related imaging cuts given in Table 2. As is clear from this Figure, the distribution is almost flat and the number of gamma-ray like events within γ -ray domain of the distribution are 120 ± 52 with a statistical significance of 2.3σ . Thereby indicating that the source was possibly in a low TeV emission state (below TACTIC sensitivity level) during the period of these observations. Moreover, when 2005 data are divided into three monthly spells I, II and III of March, April and May 2005 observations respectively and by applying the same data analysis procedure, the number of gamma-ray like events obtained are 8 ± 25 , 45 ± 31 and 67 ± 32 for the respective spells. These results which have been tabulated in Table 4 indicate that the source TeV gamma-ray signal level has remained below TACTIC sensitivity during 2005 observations.

Further, when 2005 data are analysed on nightly basis, to explore the possibility of very strong episodic TeV emission, the corresponding results obtained are depicted in Figure 5a, which shows the day-to-day variations of the γ -ray rate (γ -rays/hour) for 2005 observations. This light curve is characterised with a reduced χ^2 value of 11.99/19 with respect to the zero degree polynomial fitted constant value of 2.4 ± 1.1 photon

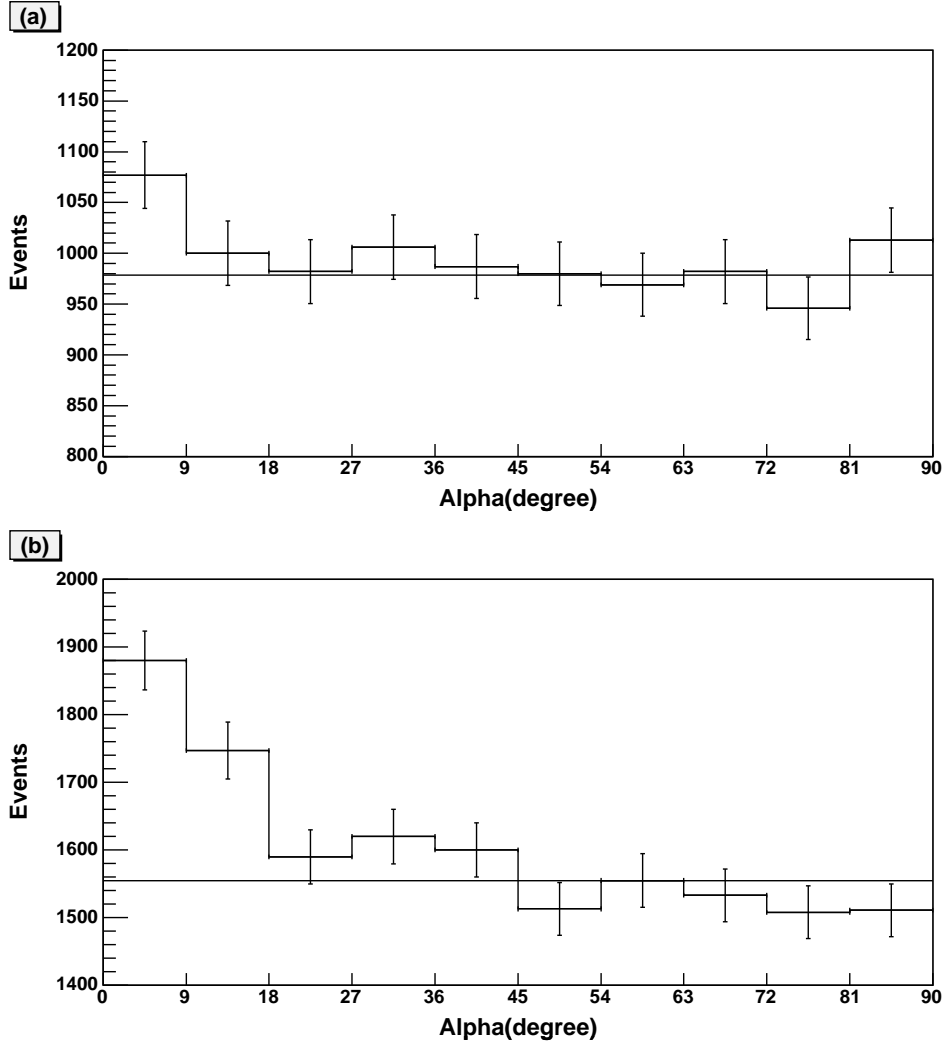


Figure 4. Distribution of image parameter ALPHA from the Mrk 501 direction (a) 13 Mar. 2005 to 12 May 2005 (b) 28 Feb. 2006 to 07 May 2006. Horizontal line represents the background level per 9° bin derived using reasonably flat α region from $27^\circ \leq \alpha \leq 81^\circ$. Error bars shown are for statistical errors only.

Table 4. Monthly spell wise analysis of Mrk 501 2005 data with statistical errors.

Spell events	γ -ray photons detected	γ -ray rate/h	Significance (σ)
I	8 ± 25	1.02 ± 3.2	0.32
II	45 ± 31	2.81 ± 1.94	1.4
III	67 ± 32	3.1 ± 1.48	2.0
I+II+ III	120 ± 52	2.64 ± 1.14	2.3

events, with corresponding probability of 0.89 which is consistent with the no- variability

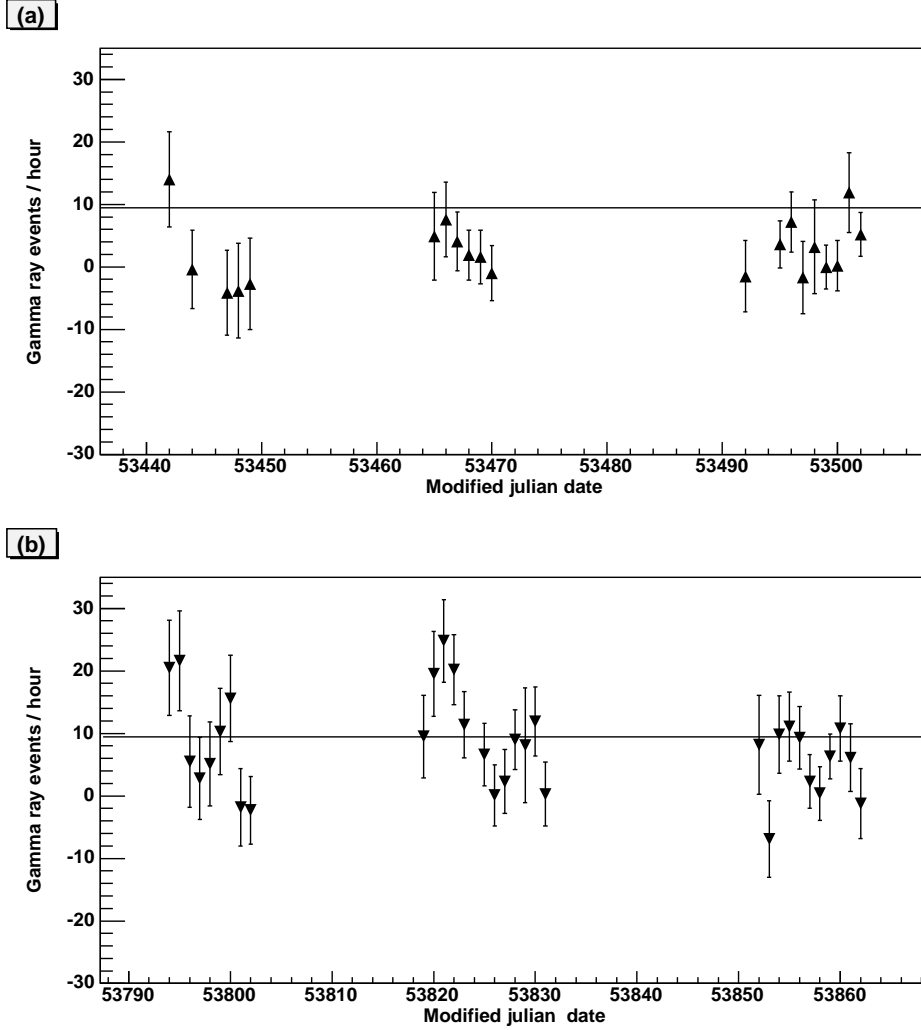


Figure 5. TACTIC lightcurve of Mrk 501 for (a) 13 Mar. 2005 to 12 May 2005 (b) 28 Feb. 2006 to 07 May 2006. Horizontal line represents the hourly γ -ray rate as detected with the TACTIC telescope from the Crab Nebula direction. Points represent nightly observed hourly γ -ray rate from the Mrk 501 direction. Error bars shown are for statistical errors only.

hypothesis. The magnitude of an excess or deficit recorded on different nights is within $\pm 2 \sigma$ level for 2005 observations and hence indicates the absence of a statistically significant episodic TeV gamma-ray signal. Further, in order to compare the VHE light curve with that of the source in the RXTE/ASM energy range 2-10 keV, we have used daily average count rates of ASM from its archived data [5], to derive the source light curve for the contemporary period and the light curve so obtained is shown in Figure 6a. This light curve is characterised with a reduced χ^2 value of 27.8/18 with respect to the zero degree polynomial fitted constant value of 0.40 ± 0.06 counts and corresponding probability of 0.06, indicating consistency with the constant flux hypothesis and no variability in a time scale of a day or more in the RXTE/ASM energy band also. We

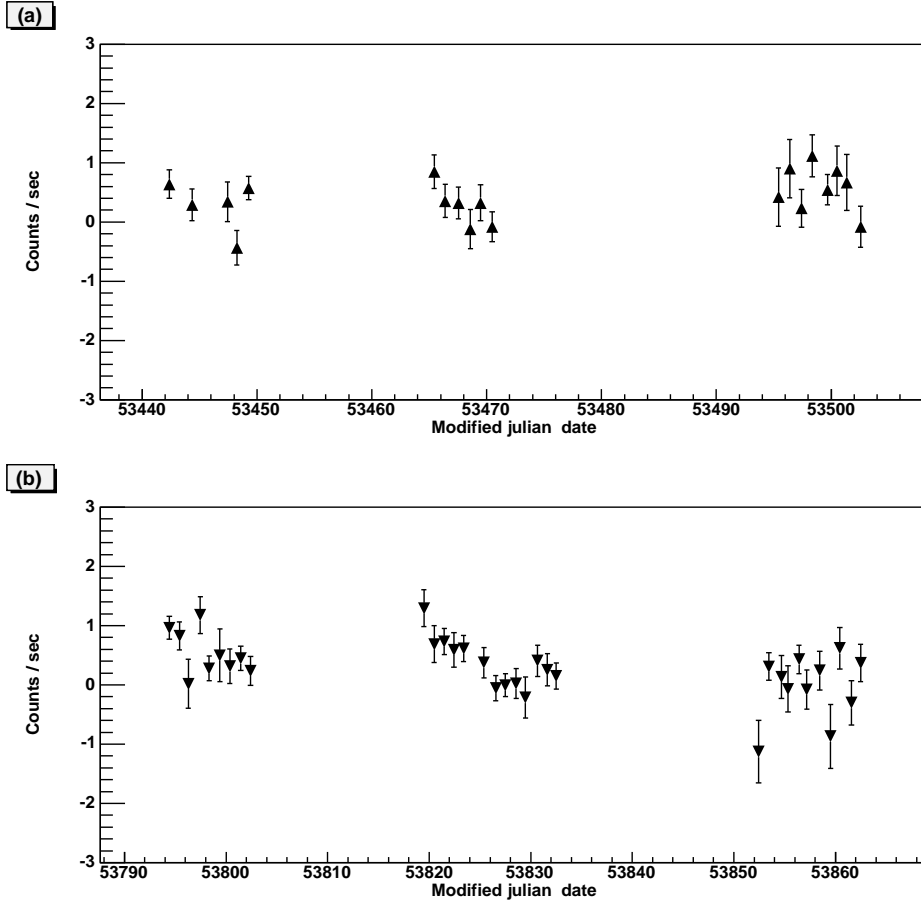


Figure 6. ASM lightcurve of Mrk 501 for (a) March 13, 2005 to May 12, 2005 (b) February 28, 2006 to May 7, 2006.

derive an upper limit of 4.62×10^{-12} photons $\text{cm}^{-2} \text{s}^{-1}$ on the VHE γ -ray emission at 3σ confidence level using the total number of 120 ± 52 gamma-ray like events obtained during 2005 observations from the source direction which is about 28% of the TACTIC detected integrated flux of the Crab Nebula above $E_\gamma \geq 1$ TeV. These results together suggest that the source Mrk 501 was possibly in a low state (below TACTIC sensitivity level) during 2005 TACTIC observations. Here, we would like to mention that the MAGIC observations on the same source during 2005 (May, 28 - July, 15 2005), wherein they have reported two episodes of strong flaring activity [4], do not overlap in time with the presented TACTIC observations which were taken between March 11 -May 12, 2005. To some extent, TACTIC 2005 observations do provide the source light curve for epochs just before the MAGIC detected two historical VHE flares from Mrk 501 on June, 30 and July, 9 2005, which have created a lot of excitement in the field.

4.4. Results of Mrk 501 2006 data analysis

Similar data analysis methodology was used while analysing data recorded, using TACTIC from the same source, during 2006 observations. When all the 2006 data are analysed together, the corresponding results obtained are shown in Figure 4b, wherein again a histogram of the alpha parameter has been plotted after having applied imaging cuts given in Table 2. This Figure shows that the distribution is not flat and the number of gamma-ray like events within the γ -ray domain of the distribution are 517 ± 69 with a statistical significance of 7.5σ . Thereby indicating that the source was in a relatively high TeV emission state as compared to that during our 2005 observations.

Next, we have divided 2006 data into three monthly spells I, II and III of February 28 to March 8, 2006, March 25 to April 7, 2006 and April 27 to May 7, 2006 observations respectively and applied the same data analysis procedure for each monthly spell. The results of this exercise have been tabulated in Table 5. The number of gamma-ray like events so obtained are 147 ± 39 , 261 ± 44 and 108 ± 33 with statistical significance of 3.7, 5.9 and 3.2σ for each spell respectively. This indicates that the TeV gamma-ray emission level of the source has brightened during II spell 2006 observations as its statistical significance is close to 6σ in 27.71 hours of observations. Further, 2006 data

Table 5. Monthly spell wise analysis of Mrk 501 2006 data with only statistical errors.

Spell events	γ -ray photons detected	γ -ray rate/h	Significance (σ)
I	147 ± 39	8.4 ± 2.2	3.7
II	261 ± 44	9.4 ± 1.5	5.9
III	108 ± 33	4.9 ± 1.5	3.2
I+ II+III	517 ± 69	7.7 ± 1.01	7.5

were also analysed on a nightly basis, to explore the possibility of a strong episodic TeV emission and the corresponding results obtained are depicted in Figure 5b. This light curve is characterised by a reduced χ^2 value of 48.8/31 with respect to the zero degree polynomial fitted constant value of 6.96 ± 0.99 counts and corresponding probability of 0.02. This indicates some variability with respect to the constant flux hypothesis in a time scale of about 24 hours. The corresponding ASM light curve of the source is shown in Figure 6b [5]. This light curve is characterised by a reduced χ^2 value of 69.5/31 with respect to the zero degree polynomial fitted constant value of 0.28 ± 0.05 counts and corresponding probability of 8.8×10^{-5} . Thereby indicating variability with respect to the constant flux hypothesis in a time scale of about 24 hours so supporting TeV observations in term of the type of variability mentioned above.

Here, we would like to mention the results of our observations during three nights of March 26, 27 and 28 , 2006 (MJD 53820, 53821 and 53822) when we find hourly

Table 6. Differential energy spectrum data for Mrk 501 in 2006 with the TACTIC telescope. Only statistical errors are given below.

Energy (TeV)	Energy bin width (TeV)	Diff. flux photons $\text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$	Statistical error in flux photons $\text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$
1.000	0.403	1.57×10^{-11}	1.28×10^{-11}
1.492	0.601	6.31×10^{-12}	1.85×10^{-12}
2.226	0.896	1.52×10^{-12}	4.62×10^{-13}
3.320	1.337	5.79×10^{-13}	1.92×10^{-13}
4.953	1.994	2.01×10^{-13}	9.20×10^{-14}
7.389	2.975	7.73×10^{-14}	4.01×10^{-14}
11.023	4.439	1.63×10^{-14}	1.92×10^{-14}

gamma-ray rates of more than two times that of the Crab Nebula. The excess of gamma-ray like events obtained are 37.0 ± 12.7 , 41.7 ± 11.7 and 56.0 ± 15.5 for 1.9, 1.7 and 2.8 hours of observations respectively. These observations possibly suggest that the source has gone into a highly active state in the VHE region during these three nights. We are not in a position to study variability features of the source on a nightly basis in the TeV domain mainly due to the poor statistics obtained with the TACTIC telescope.

4.5. Energy Spectrum of Mrk 501

We have used the 2006 data of gamma-ray like events to determine the source differential energy spectrum. The spectrum extends up to the 11 TeV with power-law index of 2.80 ± 0.27 . The details of the method used to derive the differential time-averaged energy spectrum of the Mrk 501 are given elsewhere [23].

The differential energy spectrum obtained after applying the Dynamic Supercuts to the combined 2006 data is shown in Fig. 7. A power law fit to the data ($d\Phi/dE = f_0 E^{-\Gamma}$) in the energy range 1-11 TeV yields $f_0 = (1.66 \pm 0.52) \times 10^{-11} \text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$ and $\Gamma = 2.80 \pm 0.27$ with a $\chi^2/\text{dof} = 0.773/5$ (probability = 0.97). Again a low value of the reduced χ^2 may be due to overestimation of the errors in the present measurements. The errors in the flux constant and spectral index are standard errors. We have also tried a power law with an exponential cutoff function of the form ($d\Phi/dE = f_0 E^{-\Gamma} \exp(-E/E_0)$) while fitting the observed source differential energy spectrum which, however, does not indicate any exponential cutoff feature in the energy range 1-11 TeV of the source spectrum. One of the possible reasons for not having obtained exponential cutoff in the reported source energy spectrum could be the low statistics (about 500 γ -ray like events only) detected with the TACTIC telescope.

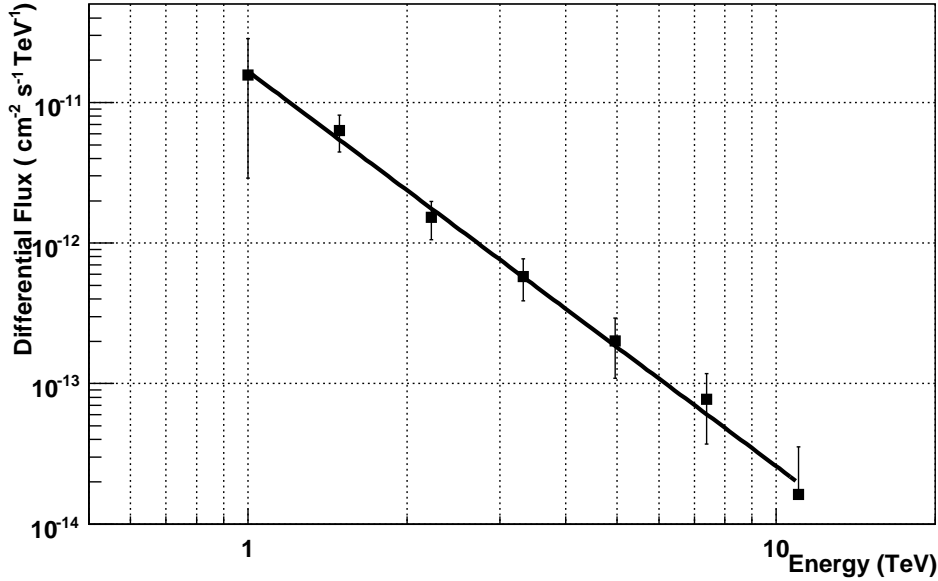


Figure 7. Differential energy spectrum of Mrk 501 obtained during 2006 observations. Error bars shown are for statistical errors only.

5. Discussion and Conclusions

We have studied the BL Lac object Mrk 501 in VHE gamma-ray energy range with the TACTIC γ -ray telescope during 2005- 06. We do not find any evidence for the presence of a statistically significant VHE gamma-ray signal either in the overall data or when the data is analysed on the month to month basis or a night to night basis during 2005 observations. An upper limit of $I(\geq 1 \text{ TeV}) \leq 4.62 \times 10^{-12} \text{ photons cm}^{-2} \text{ s}^{-1}$ (28% of the TACTIC detected Crab Nebula flux) has been placed at a 3σ confidence level on the integrated γ -ray flux. Our results do not conflict with those of the MAGIC group [4] in 2005 as the two observations are not overlapping in time as mentioned earlier. These observations rather provide the source light curve prior to the MAGIC detected two historical flares on June, 30 and July, 9, 2005.

During 2006 observations we have detected a TeV γ -ray signal from the source direction with a statistical significance of 7.5σ in 66.8 hours of on-source observations. Monthly spellwise analysis revealed that the source was relatively brighter during II spell of 2006 observations as its statistical significance is close to 6σ in 27.71 hours of observations. Data collected during three nights of March 26, 27 and 28, 2006 (MJD 53820, 53821 and 53822) do reveal hourly gamma-ray rate more than two times that of the Crab Nebula. Excesses of gamma-ray like events obtained are 37.0 ± 12.7 , 41.7 ± 11.7 and 56.0 ± 15.5 for 1.9, 1.7 and 2.8 hours of observations respectively. These observations possibly suggest that the source has gone into a variable active state in the VHE region during the observations of aforementioned three nights. We have measured

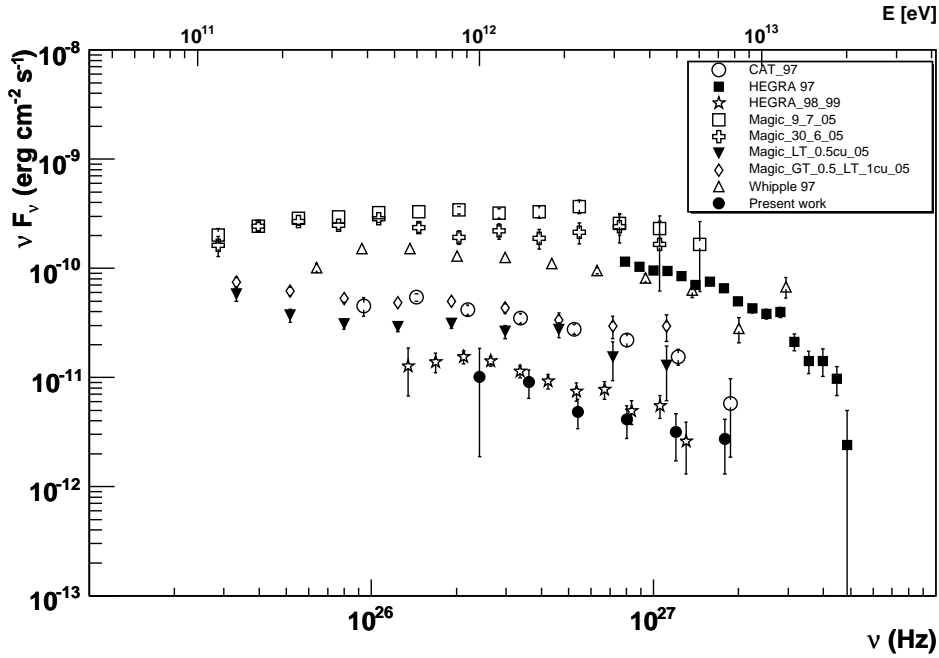


Figure 8. Comparison of VHE TACTIC derived Mrk 501 SED with those obtained during different epochs by WHIPPLE [19], HEGRA [1, 2], CAT[9], MAGIC[4] collaborations.

the source differential energy spectrum which fits well with the power law function of the form $d\Phi/dE = f_0 E^{-\Gamma}$ with $f_0 = (1.66 \pm 0.52) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ and $\Gamma = 2.80 \pm 0.27$ with a $\chi^2/dof = 0.773/5$ (probability = 0.97) in the energy range 1-11 TeV. We do not get any evidence for an exponential cutoff like feature when we use a power law function of the form $d\Phi/dE = f_0 E^{-\Gamma} \exp(-E/E_0)$ while fitting the observed source differential spectrum in the aforementioned TACTIC energy range.

In Figure 8 we compare important source related VHE spectra results obtained during different epochs by various groups, WHIPPLE [19], HEGRA [1, 2], CAT[9] and MAGIC[4]. As is clear from this figure, TACTIC 2006 results closely follow those obtained by the HEGRA group during the period 1998-99, except for the exponential cutoff feature with $E_0 = 2.61$ TeV. This source along with Mrk 421 is very interesting as it is the second nearest BL Lac object, which has been observed in highly variable states by aforementioned groups. In order to understand such highly violent extra galactic objects it is necessary to continue monitoring them for long durations with sensitive γ -ray telescopes.

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